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Abstract

Extensive experimental studies of electrically exploded 0.05- to 0.25-mm diameter metal wires and film thicknesses from 0.1 to 10 μm (coated on 0.6- to 10.0-cm diameter substrates) were made for lengths from 3.0 to 100 cm. These exploded metal-conductor-initiated discharges proved to be excellent sources for intense radiation in the near-ultraviolet range, 200 to 300 nm, with brightness temperatures measured over 40,000 K. The impedance-matching characteristics and scaling laws developed through these studies will be presented and used as a basis to compare more recent results on surface-spark discharges. These latter discharges do not appear to be as nearly blackbody as the conductor-initiated discharges, but through selected insulator surfaces, intense emission in the spectral range of interest can be obtained.

Introduction

During the past few decades there has been a growing interest in very bright incoherent optical sources particularly in the ultraviolet spectral region. Their uses center primarily around optically pumped lasers and other photochemical applications. For these purposes the xenon lamps have served admirably. They are highly efficient for converting electrical to optical energy and at 10,000 to 15,000 K are efficient radiators in the near ultraviolet spectral region.¹ However, there is a growing interest in photochemical processes requiring much brighter temperatures in the ultraviolet spectral region. Therefore, we have been studying exploding wire and film initiated discharges as high-temperature ultraviolet sources and will discuss our results in the following sections as well as some of the impedance characteristics of these nearly 40,000 K blackbody plasmas. However, an obvious drawback for these sources is the fact that a wire or film must be replaced after each discharge. For some single shot operations this may be acceptable, but many applications require higher repetition rates. This led to examination of the surface-spark discharge, which reportedly has enhanced spectral radiation around 270 nm of up to a factor of 3 by adding ZnO_2 or CrO_2 to an Al_2O_3 ceramic substrate.² We did not find significant change in the spectral irradiance by our approach to adding these metal oxides to the surface-spark discharge. However, the surface-spark discharges did produce irradiance equal to that of the exploding wire and film initiated discharges.

Exploding Wires and Films

For most of the exploding metal conductors discharges 34-cm lengths of either 0.1-mm diam tungsten wires or 1- μm thick aluminum films coated uniformly on a 1.27-cm diam acrylic resin substrate were used. The capacitor bank ranged from 10 to 40 μF charged between 27 and 47 kV and delivered up to 200 kA into the 1.47- μH circuit. When this current first begins to flow through the wire or film the metal heats, goes through phase changes to a liquid and a gas rapidly enough that it is basically inertially confined. At this time the exploding conductor becomes very resistive and the current is limited to a relatively low value. Thermal expansion eventually increases the

mean free path for the electrons leading to further ionization and avalanching. The plasma column becomes a good conductor and the current is controlled by the electrical circuit elements and the discharge dynamics.

In Fig. 1 are traces of the current and voltage measurements for the exploding film initiated discharge. Note the small "bump" of current flowing in the first microsecond. This current does all the initial exploding of the film and is the subject studied most with exploding metal conductors.³ That is why we emphasize that the discharge is *initiated* by the exploding conductor in this study. By careful analysis involving removal of both $\dot{I}(t)L(t)$ and $L(t)\dot{I}(t)$ voltages from the voltage probe measurement shown in Fig. 1, one can calculate $I(t)R(t)$ and therefore the real ohmic resistance of the discharge. The ohmic heating analysis for the standard exploding wire and film mentioned earlier were nearly identical. Approximately 40% of the initially stored electrical energy goes into ohmic heat by the time of the first current zero in this underdamped circuit. Similar analysis with critically damped xenon flash lamps shows nearly 100% of the electrical energy going into the ohmic heating during the one current pulse. However, the xenon lamp circuits stored less than 1,000 J of electrical energy and operate at peak electrical powers on the order of a few hundred kilowatts per centimeter length for a 1-cm bore lamp. On the other hand, the freely expanding exploding wire and film initiated discharges absorb tens to hundreds of megawatts of ohmic heat per centimeter of length. To first order the exploding wires/films do not expand fast enough at 1.5 km/s to absorb the ohmic heating in new gas at low temperatures and therefore, a power balance is established between the electrical power in and nearly blackbody radiation out. From $P(\text{rad.}) = A\sigma T^4$ and $P(\text{ohmic}) = I^2R$ one would predict a peak temperature for the xenon lamp of around 10,000 K and for the exploding wires/films of around 30,000 K. These temperatures are closely supported experimentally.

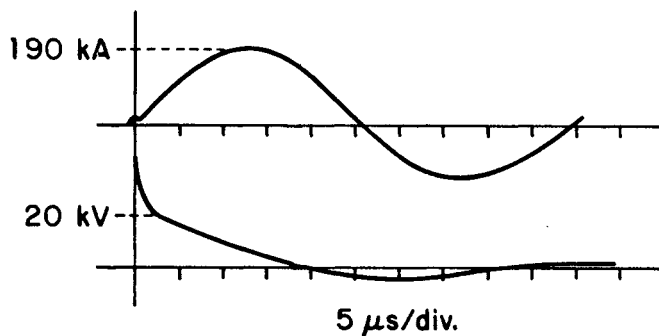


Fig. 1 Typical current and voltage traces for an exploding film initiated discharge in 2 atm SF_6 .

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From the previous discussion it appears that to increase the blackbody temperature the ohmic heating power, I^2R should be increased. For this underdamped circuit the current is approximately independent of the load and therefore we want to relate $R(t)$ to $I(t)$. Figure 2 shows this relationship as $R(t) = KI^{-1}(t)$, at $\dot{I} = 0$, where K is $6,000 \Omega \cdot A$ and $9,000 \Omega \cdot A$ for the two curves. For the 6 kV, or 175 V/cm, curve the nine data points were for 26, 36 or 47 kV charge on 10, 20 or 40 μF capacitance with the standard exploding film initiated discharge. Reducing the circuit inductance by a factor of 2 increased the voltage drop to 9 kV or 267 V/cm, where the data were taken at two different capacitor bank energies and film diameters of 6, 13 and 25 mm. Therefore, the voltage drop IR along the discharge is a constant independent of the specific current density J , amperes per unit centimeter of circumference. It is concluded from these data and other experimental results that, to first order, the ohmic heating power density in watts per cm^2 of plasma surface going into the expanding cylindrical plasma is linearly proportional to the current density $J(t)$ and to a constant $K(L_0)$ which depends inversely on the circuit inductance.

The spectral irradiance from the exploding wires and films around the wavelengths of 200, 280 and 520 nm were measured. These results are discussed in detail elsewhere and will be only briefly summarized here.⁴ In Fig. 3 are photodiode traces of the spectral irradiance at the three wavelengths showing the indicated brightness temperatures for each of the peak photodiode signals. Generally these peak brightness temperatures increase with the charge voltage on the capacitor bank, and show a broad maximum value with discharge gas pressure of SF_6 between 1 to 4 atm. Also, the temperatures increase with the current per unit circumference, J , show little dependence on wire material or film thickness, and linearly increase with the initial time rate of change in the current. Figure 4 shows the variation of the brightness temperature and irradiance for both the tungsten wires and the aluminum films versus the length of the exploding metal conductors.

These long exploding wires and films were used as bright sources to optically pump iodine lasers.^{*} We obtained 110 J from I^* at 1.315 μ and 20 J from I_2 at 342 μm using 20-cm clear optics.⁵

A need for much brighter spectral irradiance around the 280-nm wavelength was required for physics and photochemistry studies which could use shorter discharges. The discharge chamber shown in Fig. 5 was built for this purpose and could hold a 5- to 7-cm long tungsten wire between the two electrodes posts shown in Fig. 6 without the electrodes or substrate. Using 10- μF capacitance charged to 47 kV yielded a 40,000 K brightness temperature at 280 nm with approximately 5,000 K higher brightness temperatures at 520 nm and 5,000 K lower at 200 nm. These results agree reasonably well with the data in Fig. 4.

Surface-Spark

The first electrodes used in this study were finger-shaped and were separated by 3 cm. The single arc discharge formed along the insulator substrate was nearly as bright as the exploding wires for the 280- and 520-nm radiation, but the 200-nm spectral irradiance was usually much lower, often only 20% as much. Next, the 5-cm wide, 3-cm gap length geometry shown in Fig. 6 was tried. Anywhere from 1 to 4 arc channels would be evident in the open-shutter, time-integrated photographs of the discharge, but the photodiode traces suggested that the arcs were in time coincidence at least on a microsecond time scale.

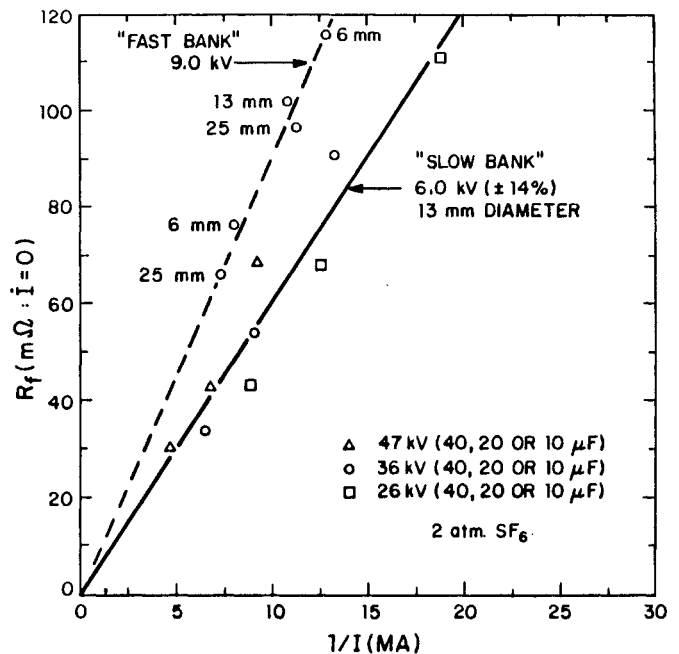


Fig. 2 The resistance of an exploding film initiated discharge for various bank energies and film diameters versus the inverse peak current.

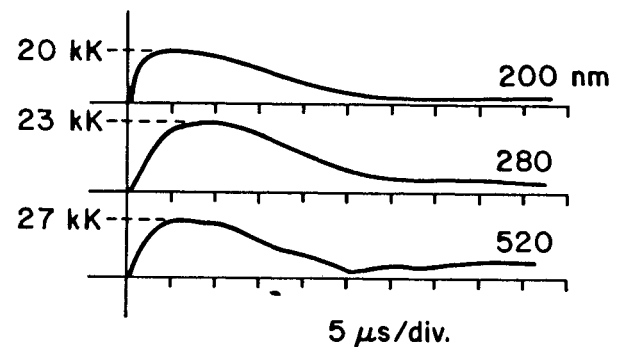


Fig. 3 Photodiode traces of an exploding film, indicating the brightness temperatures of the peaks.

The results and comparisons between the exploding wire initiated discharge and the two surface-spark discharges have been summarized in Table I. The photodiodes were located 2 m transversely from the apertures and the irradiance figures in the table assume a 50-nm bandpass around the central wavelength. The measurements were all made with 10- μF capacitance charged to 37 kV. Consider the row of 280-nm spectral irradiance data in Table I. The photodiode measured 0.16 W/ cm^2 from the exploding wire initiated discharge through a 3-mm diam aperture. Then from the same source measured 1.1 and 5.4 W/ cm^2 irradiance from the 9-mm and 30-mm diameter apertures, respectively. It is reasonable to assume, based on prior data, that the exploding wire discharges had a 35 kK brightness

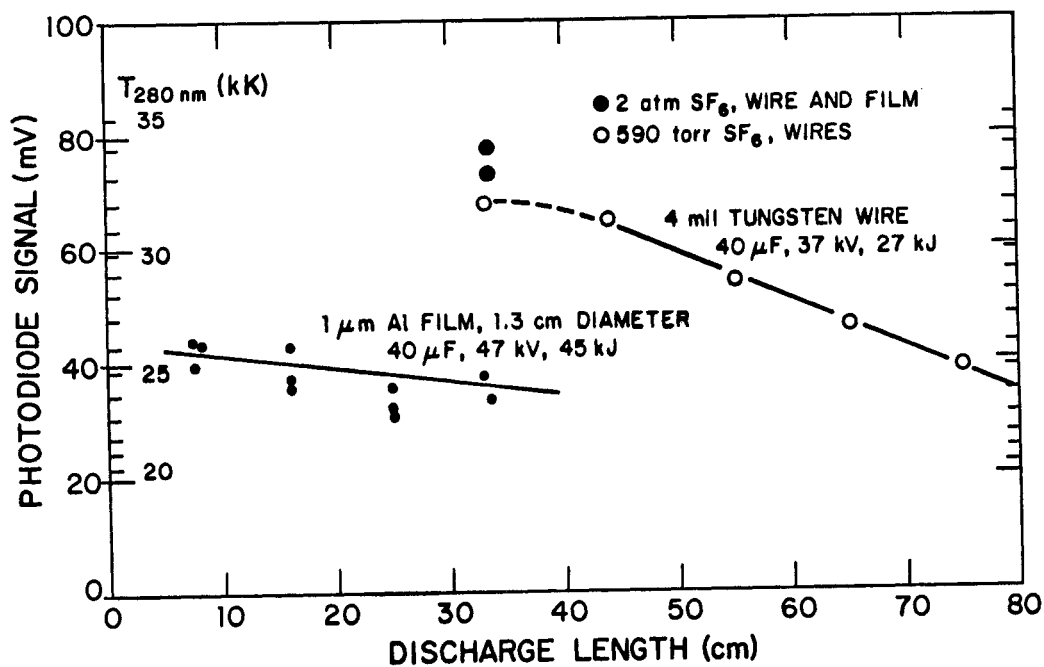


Fig. 4 Brightness temperature at 280 nm for various exploding wire/film initiated discharges versus the discharge length.

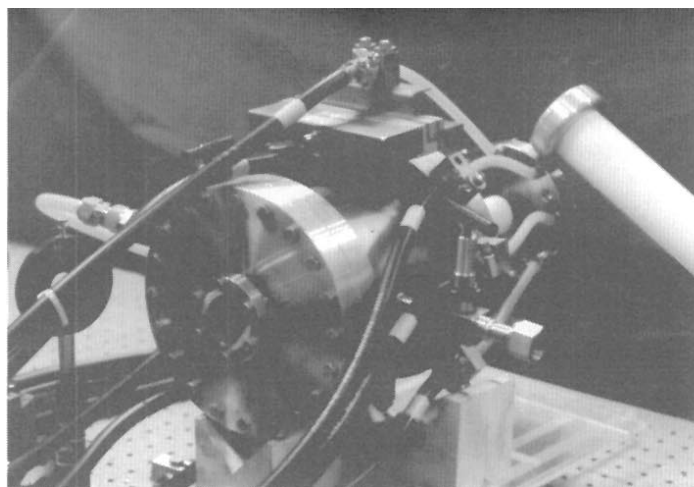


Fig. 5. Discharge chamber used for short wires and the surface-spark discharges.

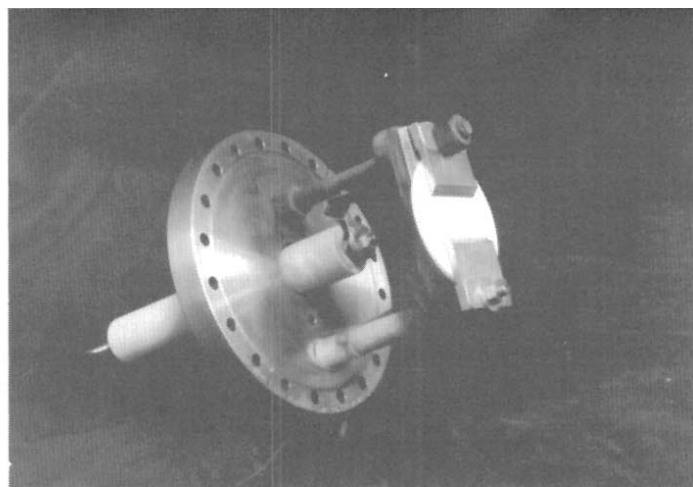


Fig. 6 The surface-spark discharge electrodes, 5-cm wide with 3-cm gap on an alumina substrate.

TABLE I

THE SPECTRAL IRRADIANCE AT 2 m FROM DIFFERENT DISCHARGES FOR A 50-nm BANDPASS

	EXPLODING WIRE DISCHARGE			SURFACE-SPARK DISCHARGE			
	7-cm LONG			FINGER ELECTRODES 1.4 cm GAP	5cm WIDE ELECTRODES 3-cm GAP		
	APERTURE DIAMETER			APERTURE DIAMETER	APERTURE DIAMETER		
	3-mm	9-mm	30-mm	3-mm	9-mm	30-mm	30-mm
200 nm	0.28 (30 kK)	1.8	8.0	0.04 (16 kK)	0.69	12	8.5
280 nm	0.16 (35 kK)	1.1	5.4	0.16 (34 kK)	1.4	4.7	6.3
520 nm	0.03 (40 kK)	0.19	1.1	0.02 (33 kK)	0.21	1.3	1.4

UNITS OF W/cm²

temperature in all three discharges at 280 nm and 30 kK and 40 kK at 200 and 520 nm, respectively. Then with the small electrodes surface-spark discharge the irradiance at 280 nm from a 3-mm diam aperture was also 0.16 W/cm², or equivalently 34 kK. However, notice the 200-nm irradiance with this discharge was substantially less than the exploding wire case. Then finally the last two columns with the 5-cm wide electrodes and 3-cm gap surface-spark discharges show the spectral irradiance with the 30-mm aperture at all three wavelengths to be the same as with the exploding wire initiated discharge.

Spectroscopy of the emission from these surface discharges shows that the radiation is non-Planckian, in contrast to the exploding wire initiated discharges. Time-integrated spectrograms over the range 200-500 nm taken with a 0.5-m focal-length spectrograph show that the line emission predominated over a range of discharge energy, with various gas fills, and over a range of ceramic surface conditions. The spectrum of the emission depended strongly on the dielectric surface material, but very little on the fill gas type. Tentative identification shows that spectra to be comprised of atomic emission from surface constituents.

Conclusions

The surface-spark discharge appears to be capable of high irradiance especially in the near ultraviolet-spectral region, comparable to that of the much brighter exploding wire/ film initiated discharges. This will prove to be a useful tool for many physics

and photochemistry experiments where many discharges are desirable. It also seems evident that further enhancement is available through selected surface conditions.

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